CAPACITY AND LEVEL OF SERVICE OF SIGNALIZED ROUNDABOUTS IN URBAN INDIAN CONTEXT

RAKESH KUMAR 111CE0499

DEPARMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA-769008

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By

RAKESH KUMAR

111CE0499

Under the Supervision of

Prof. Prasanta Kumar Bhuyan

DEPARMENT OF CIVIL ENGINEERING

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National Institute of Technology, Rourkela

CERTIFICATE

This is to certify that the Thesis Report entitled **"CAPACITY AND LEVEL OF SERVICE OF SIGNALIZED ROPUNDABOUTS IN URBAN INDIAN CONTEXT"** submitted by Mr. **RAKESH KUMAR** bearing roll no. **111CE0499** in partial fulfilment of the requirements for the award of Bachelor of Technology in Civil Engineering during session 2011-2015 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Prof. Prasanta Kumar Bhuyan
Assistant Professor
Dept. of Civil Engineering
National Institute of Technology
Rourkela-769008

Place:

Date:

Dedicated to

To My Parents, My Sisters, All Family Members, My friends & Teachers whose efforts, sacrifice, patience, inspiration, and encouragement are helping me to move forward.

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Rakesh Kumar

Date: Roll No: 111CE0499

Place: Dept. of Civil Engg.

NIT, Rourkela

ABSTRACT

Modern roundabouts, first installed in England in the early 1960s, are becoming popular substitutes for signalized intersections in India. These facilities were originally introduced in order to solve the problems of the existing rotaries and traffic circles. This thesis presents a formulation for evaluating the capacity, delay, and level of service of multilane signalized roundabouts. Based on the study of available literatures, the formulation uses the gap acceptance theory and evaluates entry lanes on a lane-by-lane basis. Besides circulating and exiting flows, number of lanes and lateral position of the vehicles, as they approach and cross the roundabout, showed significant influence on roundabout entry capacity. Substantial differences in capacity estimates were observed between various considered methods. It is quite essential to calibrate such methods to meet regional needs. This study describes a new model for capacity estimation and level of service analysis of signalized roundabouts derived under heavy demand conditions at large roundabouts. The capacity estimation models, FHWA, IRC & SIDRA shown that the selected roundabout are under saturation condition and the Level of Service (LOS) was found out to be satisfactory.

KEY WORDS

Signalized Urban Roads, Capacity Analysis, Level of service (LOS), Delay, Queue, Gap Acceptance method, Geometric Features and Opposing Flow Rate.

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Chapter 1

Introduction

1.1 General

Roundabouts are the intersections of two or more roads that are made up of one-way circulating roadway that give priority over the approaching traffic. The approaching traffic is controlled by traffic signs, and can only make a left turn onto the circulating headway. The only decision that the motorist needs to make while reaching the yield line is whether or not the gap in circulating traffic is large enough for them to enter. The vehicles then easily exit the circulating roadway by making a left turn towards their destination. The necessity of the roundabout is that the traffic is required to slow down for negotiating the curve around the central island. In most cases, modern roundabouts have been found to be much safer than other intersections. The reduction of points of conflict from 32 to 8 lessen the chances for crashes, and when combined with reducing speed, crash probability is further reduced.

There are three main characteristics of roundabouts that identify them when compared to traffic circles:

1. Yield-at-entry or offside priority – Roundabouts provide vehicles in the circulatory roadway with the right of way. This is quite different than other uncontrolled, yield controlled or multi-way-stop controlled intersections that give priority to the vehicles already in the facility, these roundabouts control the entering vehicles not with a stop signs or traffic signals but with a yield sign.
2. Approach flare – Roundabouts, mostly, approach flare out at the entries and allow the entrance of more vehicles to the circulatory roadway at more obtuse angles. This increases capacity, and allows the vehicles to enter at reduced and similar speeds as

the circulating vehicles. The angle and size of the flare is controlled generally by a raised splitter island that separates all the entering and exiting traffic at the approach. This island also provides the pedestrians a safe way to cross the approach in stages.

3. Deflection – This characteristics is related to the geometry of the roundabout that requires vehicles to slow down while maneuvering through the roundabout. The diameter of the central island and the angle of entry determine the potential speeds and deflection of circulating and entering vehicles.

The overall framework of this study is illustrated in Figure 1.1

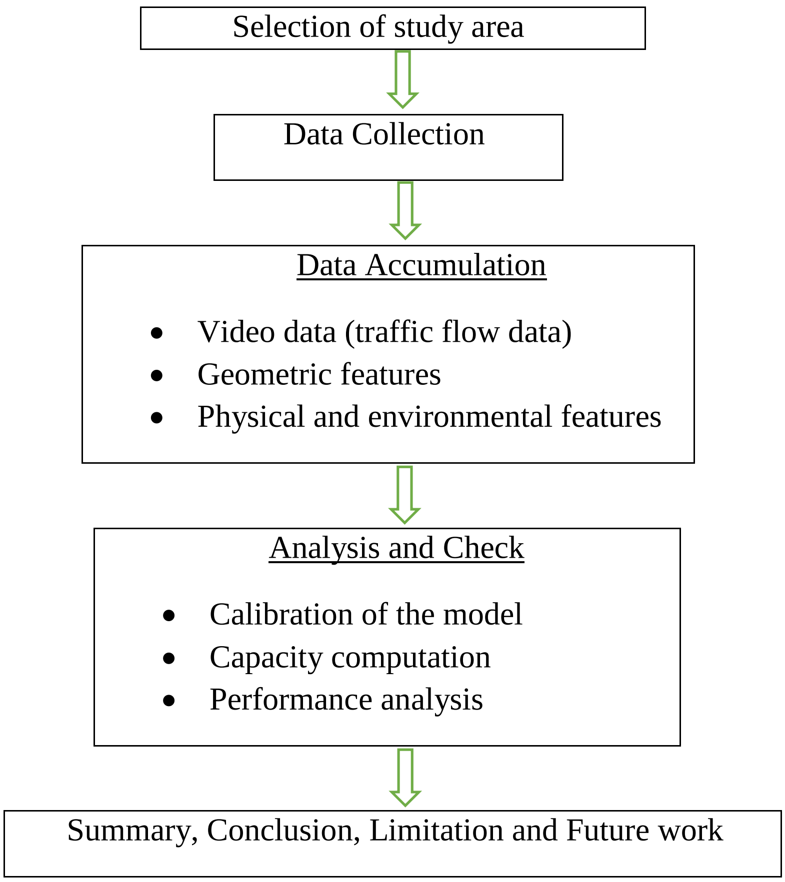


Figure-1.1: Overall Framework of the study

1.2 Statement of the Problem

The purpose of this study is to analyze the capacity and performance of signalized roundabout to find out possible effective and cheaper way to resolve the traffic congestion problem in short term or interim basis for urban Indian context. This is done by determining the capacity, Level of Service (LOS), queue length and delay of a multilane roundabout with the application of several methodologies. The primary problem that has been of the concern is to determine which of the used methodologies are most appropriate. Different types of methods have been used. Some methods analyze the roundabout based on all the entry lanes of an approach, some treat each lane as its own entity, and some use a lane-by-lane analysis based on several factors. Certain models are based on the gap acceptance principles, while others are based on empirical regression formulas by considering the geometry and traffic flow characteristics at roundabouts.

A gap acceptance method determines capacity of a roundabout using a minimum follow up headway and critical gap required by a driver while attempting to enter the circulating stream of traffic. The regression model determines the capacity based on certain geometrical and environmental characteristics of the roundabout and the circulating flow. This type of model is calibrated using empirical data from roundabouts at saturated capacity conditions. The LOS for modern roundabouts is very important for the analysis of urban streets. The LOS affects the design, planning and operational aspects of several transportation projects as well as the provision of limited financial resources among certain competing transportation projects.

Traffic following lane discipline and composed of identical vehicles is termed as homogeneous traffic. Traffic composed of motorized and non-motorized two-wheelers and three-wheelers along with other types of vehicles with no-lane discipline, is termed as heterogeneous. This heterogeneous traffic is quite different from the one having the presence of trucks and has also been termed as heterogeneous traffic. Since India is a developing country and no suitable method is yet to analyze the heterogeneous traffic of signalized Indian roundabouts.

1.3 Objectives and Scope

Based on the above problem statement, the objectives of the study are:

- To estimate the capacity and corresponding degree of saturation using several calibrated methodologies to check the operational efficiency of the signalized roundabouts.
- To compare the output given by different models using the field data.
- To assess the performance behavior by finding out the average control delay, queue length and Level of Service (LOS) for each approach leg of roundabout considered.

1.4 Organization of Report

The report describes about six chapters. The first chapter compromises introduction to research work and detail description about statement of the problem, objectives and scope of the study. The second chapter is literature review part which includes the level of service, use of GIS-GPS in traffic data collection and clustering techniques. Third chapter provides idea about the study area of this work and methodology of data collection. The forth chapter is for detail description on cluster techniques. Result and analysis for the research work is found out in the chapter five. The summary and conclusion are in the chapter six and it also includes the limitation and scope for the future work.

Chapter 2

Literature Review

2.1 General

Since the introduction of the modern roundabouts in the early 1960s, many different types of models have been developed for determining the roundabout capacity and Level of Service. This part of the paper addresses several different approaches used to determine roundabout performance. The literature review will go through the different theories upon which these models are based, and the various equations that use a series of variables and parameters for estimating capacity and delay. These models have been developed in many countries, but primarily from Australia and Western Europe.

Many of the models constitute elements of different software technologies that evaluate roundabouts and traffic corridors or network at microscopic or macroscopic levels. With the theories discussed in this literature review, it will be easier to determine which characteristics of roundabout performance estimation should be used for developing a model for determining the capacity and Level of Service (LOS) of Indian roundabouts for implementation into traffic forecasting models.

There are several features used to identify roundabouts apart from traffic circles and rotaries. Wallwork (1997) describes traffic circles as the one having square entries, and use stop control of the entry. Flannery, et al (1998), Myres (1994), and Bared and Oursted (1995) state three main characteristics of roundabouts as: yield at entry, flared entries and deflection. In addition to these characteristics, defined previously, Ray and Rodegerdts (2001) also identified other elements that distinguish modern roundabouts from other circulatory roadway facilities. These elements include parking availability, pedestrian access and crossing location and the circulation direction on the roadway.

Stuwe (1991) developed a formula for calculating the capacity of roundabouts. These formulae were developed by use of an empirical procedure and regression techniques. Therefore, traffic flow at several roundabouts was observed and recorded by video equipment. Based on the assumption that the entry flow was saturated, traffic flow of entering and circulating vehicles were analyzed and counted in 1 minute intervals. Based on these data samples, a provisory formula has been developed for the prediction of roundabout capacity. Chodur, J. (2005) did a detailed study on the Poland roundabouts and analyzed the parameters with respect to polish conditions. Studies were conducted in several Polish cities and towns to analyze capacity of the movements at stop-controlled two way intersections, at roundabouts and two-way yield-controlled intersections. The results have allowed the development of basic capacity parameters, i.e. follow up headway and critical gap and models calibration to local conditions.

Mereszczak et al. (2006) did a detailed study on the effects of exiting traffic and width of Splitter Island on the capacity of roundabouts in United States. The studies showed that the capacity determined considering the effect of exiting traffic gives much more improved prediction of the actual capacity of the roundabouts over the estimates without considering it. Zhaowei and Yuzhou (2008) analyzed the existing capacity models and proposed an outlook on roundabout capacity and focused on the problem research principles and methods such as empirical regression model, gap acceptance model and model based on simulation software. Determining the interaction mechanism among each traffic flow and considering the significant impact factors, the capacity model is established on the whole.

Grenard and Shah (2011) presented a paper on a streamlined process to develop capacity models for communities with congested roundabouts. The process consists of video data collection, data processing and verification, and model development. The process was applied to a case study of three roundabouts in Carmel, Indiana. Overall, the streamlined process to develop capacity models for local roundabouts proved valuable, and it can be scalable according to available resources. The capacity models developed by this process are based on actual flow rates at local congested roundabouts and will provide an accurate capacity estimation for planning new roundabouts or capacity improvements. Akcelik (2011) studied the control of the roundabouts using materials signals and describes the basic concepts of the analytical model of the operation of roundabouts with these metering signals. The model estimates the capacities and performance measures (average control delay, queue length, stop time and so on) of the controlling and metered approaches of the modern roundabout as well as other approaches which operate under normal roundabout entries.

Hagring and Rouphail (2003) investigated two-lane roundabout in Copenhagen, Denmark and the collected data enabled the estimation of follow-up headway, critical gap, and delay and entry capacity. The basic objective of this research was the evaluation of the need for more complex capacity models than existing currently in order to properly represent gap-acceptance behavior of driver at multilane roundabouts. The complexity arises when drivers are assumed to accept pairs of critical gaps in the inner and outer circulating lanes simultaneously before entering the roundabout. This approach requires the independent evaluation of the circulating- lane headways and critical gaps and not to superpose in a single traffic stream unlike most current capacity guides assume. This approach also implies that there is considerable impact of circulating-lane volume allocation on entry capacity. The field results indicated that though there were differences in the gap-acceptance behavior of drivers entering in the right approach lane, with critical gaps estimated at 4.49 s and 3.67 s for the outer and inner circulating lane, respectively, at the site. Finally, the allocation of lane of circulating flow had a significant impact on capacity, especially at large circulating-flow rates. This implies that the origin and destination of the flow comprising the circulating traffic must be accounted for capacity estimation.

Wang and Chen (2007) studied the differences on capacity and delay performance of two 2-lane streets intersections between two-way stop-controlled (TWSC) types, all-way stop-controlled (AWSC) types and roundabouts under different flow patterns based on mathematic models. The TWSC intersection has some advantages as low delay of minor street are higher and it also shows inefficient under balanced flow pattern. The AWSC intersection shows good performance in the case of unbalanced flow patterns and high left-turn percentage, but it has a low capacity and bad performance of anti-disturbance.

Bie and Lo (2006) estimated the entry capacity of each lane using the lane utilization analysis for multi-lane roundabouts. The reserve capacity was then used as a measure to assess the overall roundabout performance. This paper also showed the sensitivity of driver’s lane choices on the overall capacity of traffic roundabouts. Polus and Shmueli (2011) analyzed the geometric data and traffic flow from six small to medium-sized roundabouts and the calibration of individual and aggregated entry-capacity models were done by using the circulating flows and diameter as explanatory variables. A faithful agreement between the latest Highway Capacity Manual model and the model developed for right-turn capacity at a signalized intersection was obtained by substituting conflicting flow over circulating flow.

Bared and Afshar (2009) planned the capacity models for two lane and three-lane roundabouts by separate entry-lane and separate circulatory-lane traffic volumes. VISSIM micro simulation software was used to compare with the new NCHRP models as well as SIDRA and Tanner-Wu models. Shao and Sun (2010) categorized LOS into two parts: Level of facility supply and Level of traffic operation. Travel speed to free flow speed ratio was considered as evaluation index of traffic operation. Traffic operation categorized into different groups using Fuzzy set.

2.2 Performance Estimation Parameters

Roundabout capacity and Level of Service analysis can be performed at several levels of detail. Akcelik (1998) mentions three methods of capacity measurement. These include analysis by total traffic approach flow data. There is analysis by used for signalized intersections in the United States HCM by lane groups and there is lane-by-lane analysis, which is used in SIDRA. For the purpose of allowing improved geometric modeling of the intersection, Akcelik used the lane-by-lane method. He points out the importance of recognition of unequal lane utilization, because of its effects on the capacity and performance of the roundabout. Akcelik described that using dominant and subdominant lanes is the best way to account for unequal lane use.

Fisk and Akcelik both recommended using a different follow up headway and critical gap for each lane. This is appropriate for the methodologies being presented, because the vehicles using the left lane must essentially find a gap in the outside circulating lane at the same time it attempts to enter the gap in the inside circulating lane. The question then surfaces as how to determine what vehicles use which lane. As Akcelik (2001) suggested, a satisfactory capacity and Level of Service formulation should include modeling geometry and driver yield behavior. The driver yield behavior is accounted for in the delay equations and gap acceptance-based capacity. The geometry delay is accounted for the design of the roundabout using the travel forecasting model. This section will discuss the additional parameters and postulations that will be included in the product of this thesis; analyzing capacity and Level of Service.

2.3 Critical Gap and Follow up Time

There are a variety of thoughts of what is the most appropriate critical gap for vehicles entering a roundabout. Considering that traffic at a stop can perform three maneuvers: right turn, left turn and through, different sized gaps would be far more better than in a roundabout where all motorists are taking a single turn into the circulating roadway. Therefore by the idea that if a single critical gap can be used for three maneuvers, it would only be more accurate for one maneuver. Vehicle type and approach grade, Geometry, turning movements, were found to affect follow up time and critical gap. The delay by a motorist was also found to be a major factor affecting a gap acceptance tendencies of motorist. Akcelik (1998) introduced flow-based formulations that determine the follow up time and critical gap. Akcelik documented a follow up headway of 1.2 to 2.4 seconds and a critical gap range of 2.2 to 8.0 seconds. To determine the appropriate magnitude of these parameters the subdominant and dominant lanes approach was used.

The Transportation Research Board (HCM 1997) presents its follow up time as 2.6 to 3.6 seconds and critical gap range as 4.1 to 4.6 seconds. However, these values are for only single lane roundabouts. List et al (1994) determined the average the follow up time to range from 1.8 to 3.7 seconds and critical gap to be from 2.8 to 4.0 seconds. These values were most representative for the right lane. All these gaps are considerably smaller than the recommended critical gaps and follow up times for two-way stop controlled intersections. Roundabout follow up times and critical gaps are smaller due to two reasons. The first is the ability of some vehicles to enter the circulating roadway without coming to a complete stop. If there are no queued vehicles in the entry lane, the yield control allows vehicles to only reduce to the speed at which they can safely negotiate the roundabout. The second reason is the flare of the roundabout.

Chapter 3

Study Area and Data Collection

This section dissevered into two parts. The first part concisely depicts the study corridors from where the speed data as well as the road inventory data were accumulated. The second part clarifies the contingents of data accumulation technique espoused for this study.

3.1 Study Area

An important urban signalized road intersection of the city Thiruvananthapuram of Kerala state, India is picked out for this study. The map of the considered roundabout is as shown in the figure 3.1 below:

Figure- 3.1: Map showing selected roundabout of Vazhuthacaud square, Trivandrum

3.2 Data Collection

A digital camera was installed on a building beside the south approach leg of the selected roundabout from where movement of the vehicles through each of the legs was visible and recorded. The data was recorded for 1 hour during peak flow of vehicles. The different geometric features of the selected roundabout was taken such as carriageway of each of the approach leg, entry width, width of the weaving section, width of non-weaving section, length of weaving section, diameter of weaving section etc. From the 1 hour data, number of different types of vehicles like heavy vehicle, cars, autos, two wheelers was found out.

3.2.1 Traffic flow data:

From the considered roundabout, the number of all types of vehicles such as heavy vehicles, light vehicles and two wheelers were found out for each of the approach leg of the roundabout as shown in the table 3.1 below:

Table 3.1: 1 hour traffic flow data

Roundabout	Leg No.	Heavy Vehicles	Light Vehicles		Two Wheelers
			Cars	Auto	
Vazhuthacaud Square, Trivendrum	N	6	362	219	783
	S	52	657	486	1530
	E	0	176	58	257
	W	43	425	358	1034

3.2.2 Geometric features:

The geometric characteristics such as carriage way of approach road, entry width, width of the weaving and non-weaving section, length of weaving section, of the selected roundabout was measured which are as shown in the table 3.2 below:

Table 3.2: Geometric features of the roundabout

Roundabout	Leg No.	Carriage way of approach road	Entry Width	Width of non-weaving section	Width of weaving section	Length of weaving section	Diameter of central island
Vazhuthacaud Square, Trivandrum	N	16.70	8.0	9.30	10.2	32.55	24
	S	14.82	9.4	9.5	13.25	34.57	24
	E	15.85	9.1	10.10	15.5	27.54	24
	W	14.85	9.9	9.0	14.6	23.43	24

3.3 Summary

This chapter provided the details of the study area, data collection and database preparation. The details of roundabout on which 1 hour video data was collected were discussed. The next chapter gives idea about the different methodologies used to find out the capacity and performance analysis.

Chapter 4

Analysis Methodology

4.1 Data Processing

The video data which was collected from the selected roundabout was processed. The number of each type of the vehicles from each of the approach leg was calculated. The number of vehicles found was converted into PCU.

PCU stands for Passenger Car Unit which is a measure of the relative space necessity of a vehicle class compared to that of a passenger car under a specified category of traffic, roadway and some other conditions. If the addition of a particular vehicle of a particular class in the traffic stream produces the same effect as that due to the addition of one passenger car, then that corresponding vehicle class is equivalent to the passenger car with a PCU value equal to 1.0. The suggested PCU value for urban roads is shown in the table 4.1 below:

Table 4.1: PCU values of different vehicle classes

S. No.	Vehicle class	PCU values of vehicle classes at:		
		Urban roads, mid-block sections	Signalized intersection	Kerb parking (parallel & angle)
1	Car	1.0	1.0	1.0
2	Bus and truck	2.2	2.8	3.4
3	Auto rickshaw	0.5	0.4	0.4
4	Pedal cycle	0.7	0.4	0.1
5	Bullock cart	4.6	3.2	1.2
6	Two wheeler	0.4	0.3	0.2

The PCU value of a vehicle class may be considered as the ratio of the capacity of a roadway when there are passenger cars only to the capacity of the same roadway when there are vehicles of that class only.

4.2 Estimation of Critical gap & Follow up headway:

Critical Gap/Headway:

The minimum time interval which is required in circulating flow when an entering vehicle can safely enter the roundabout is called critical gap. In theory, gap accepted by a driver is greater than or equal to his/her critical gap; a rejected gap is smaller than the critical gap. Critical gaps are estimated based on the quantified rejected and accepted gaps, and the point where accepted and rejected gaps are equally possible.

Follow Up Headway:

The minimum headway between two entering vehicles, when two vehicles accepting the main stream headway under a queued condition is called follow up headway. It is the inter vehicle headway on an approach at capacity.

Method used for estimating Critical gap:

INAFOGA **METHOD:**

Satish et al in the year of March 2011 presented another idea for measuring critical gap making utilization of clearing conduct of vehicles in conjunction with gap acceptance information. He proposed an area named as INAFOGA (Influence Area for Gap Acceptance) which had a dimension of L*W, where L= 3.5 m (lane width) & W= 1.5 times width of crossing /merging vehicle. The method considers the clearing behavior of a vehicle (clearing time is the time taken by the minor street/U-turn vehicle to clear the influence area) & gap acceptance behavior.

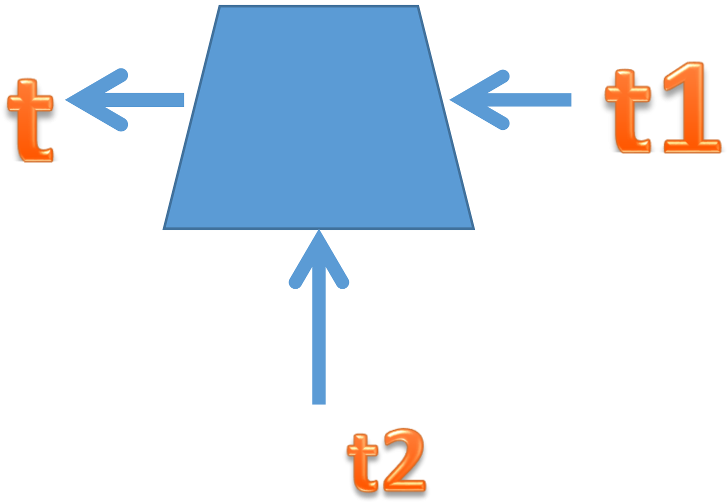


Figure 4.1: INAFOGA method diagram

Where,

t1 = Front bumper of first vehicle in circulating flow

t2 = Front bumper of first through vehicle in the approach leg

t = time instant for back bumper touches the boundary

Characteristics of the "INAFOGA":

i. A vehicle taking right turn from Minor Street waits at the stop line near INAFOGA & is said to clear the crossing point when its last part crosses the stop line in the major street.

ii. Distinction between landings of continuous major road vehicles at the upstream end of the INAFOGA is considered as 'Gap'

iii. In this method, a typical cumulative frequency distribution curve for clearing time of a minor street vehicle against its corresponding Lag & Gap Acceptance curve is plotted obligating a common point of intersection. This point of intersection indicates the minimum/critical gap sufficient for the vehicle to enter the INAFOGA keeping in mind the safety aspect.

The critical gap and the follow up headway for each of the approach leg is as shown in the table 4.2 below:

Table 4.2: Critical gap and follow-up headway of each approach leg

Roundabout	N		S		E		W	
	Critical gap (sec)	follow up time (sec)	Critical gap (sec)	Follow up time (sec)	Critical gap (sec)	Follow up time (sec)	Critical gap (sec)	Follow up time (sec)
Vazhuthacaud square, Trivandrum	3.28	2.43	3.53	2.49	3.17	2.33	3.69	2.47

4.3 Methods used for Capacity Analysis:

To analyze the selected roundabout, different methodologies have been used in this paper.

4.3.1 FHWA Method:

The FHWA Roundabout Guide (B7) presents three capacity formulas for estimating the performance of roundabouts. These were intended for use as provisional formulas until further research could be conducted with US data. The FHWA method for urban compact roundabouts is based on German research (B8) and is given as follows:

$$Q_{c,max} = 1218 - .74q_c \text{ , for } 0<Q_c<1646$$

Where, $Q_{c,max}$ = maximum entry flow (veh/h)

Q_c = traffic flow on the circulatory roadway (veh/h)

The FHWA method for single-lane roundabouts is based on the UK's Kimber equations (B9) with assumed default values for each of the geometric parameters. In addition, an upper cap to the entry plus circulating flow of 1800 veh/h was imposed. The resulting equation is given as follows:

$$Q_{c,max} = \min\begin{bmatrix} 1218 - 0.5447Qc \\ 1800 - Qc \end{bmatrix}, \text{ for } 0<Q_c<1800$$

Where: $Q_{c,max}$ = maximum entry flow (veh/h)

Q_c = traffic flow on the circulatory roadway (veh/h)

The FHWA method for double-lane roundabouts is also based on the Kimber equations with assumed default values for each of the geometric parameters. The resulting equation is given as follows:

$$Q_{c,max} = 2424 - 0.7159Q_c \text{ , for } Q_c > 0$$

Where: $Q_{c,max}$ = maximum entry flow (veh/h)

Q_c = traffic flow on the circulatory roadway (veh/h)

4.3.2 IRC Method:

According to the IRC method of capacity estimation of a roundabout, the capacity of a roundabout is calculated by the capacity of each of the weaving sections. The following empirical formula has been proposed by Transportation road research lab (TRL) to find out the capacity of the weaving section.

$$Q_w = \frac{280w\left[1+\frac{e}{w}\right]\left[1-\frac{p}{3}\right]}{1+\frac{w}{l}}$$

Where e is the average exit and exit width, i.e., $(e_1 + e_2)/2$, w is the length of the weaving section, l is the length of weaving, and p is the proportion of weaving to the non-weaving traffic. If b and c are the weaving traffic and a and d are the non-weaving traffic, then,

$$P = \frac{b+c}{a+b+c+d}$$

This formula for capacity is only valid when the following conditions are satisfied.

1. Weaving width of the roundabout is in between 6 and 18 meters.
2. The ratio of the average width of carriage way at entry and exit to the width of the weaving section is in the range of 0.4 to 1.
3. The ratio of width to the length of the weaving section of the roundabout is in between 0.12 and 0.4.

4. The proportion of the weaving to the non-weaving traffic in the roundabout is in the range of 0.4 to 1.
5. The length of the weaving section available at the intersection is in between 18 to 90m

4.3.3 AKCELIK Methods:

A method for treating the traditional gap-acceptance modelling used for roundabouts and signalized intersections by analogy to traffic signal operations was conceived by Akcelik (1991). According to Akcelik, all capacity and performance calculations are carried out for individual lanes of entry (minor) movements, but traffic in all lanes of the major (conflicting) movement is treated together as one stream. When there are several conflicting (higher priority) streams at signalized intersections, all conflicting streams are combined as one stream. The resulting total opposing flow rate, q_m may be expressed in passenger car units (pcu) allowing for the effect of heavy vehicles in the opposing streams. In the following equations, q_m is in veh/s or pcu/s.

Average durations of block and unblock periods (seconds):

$$t_b = e^{\frac{\lambda(t_c-\Delta_m)}{\varphi q_m}} - \left(\frac{1}{\lambda}\right)$$

$$t_u = 1/\lambda$$

Average effective blocked and unblocked times (seconds):

$$r = t_b - t_f + l = e^{\frac{\lambda(t_c-\Delta_m)}{\varphi q_m}} - \left(\frac{1}{\lambda}\right) - t_f + l$$

$$g = t_u + t_f - l = (1/\lambda) + 0.5t_f$$

Where $l = 0.5t_f$

Average gap acceptance cycle time (seconds):

$$c = r + g = e^{\lambda(t_c-\Delta_m)/(\varphi_m q_m)}$$

Unblocked time ratio:

$$u = g/c = \left(1 - \Delta_m q_m + 0.5\varphi_m q_m t_f\right)e^{-\lambda(t_c - \Delta_m)}$$

Entry stream saturation flow rate, s (veh/h):

$$s = 3600/t_f$$

Gap-acceptance capacity (veh/h):

$$Q_g = s\,u = (3600/t_f)\,u$$

$$= (3600/t_f)\left(1 - \Delta_m q_m + 0.5\varphi_m q_m t_f\right)e^{-\lambda(t_c - \Delta_m)}$$

Entry stream capacity (veh/h):

$$Q = \max(Q_g, Q_m)$$

where Q_m is the minimum capacity (veh/h) given by:

$$Q_m = \min(q_e, 60\,n_m)$$

Where q_e is the entry stream flow rate (veh/h), and n_m is the minimum number of entry stream vehicles that can depart under heavy major stream flow conditions (veh/min).

The gap-acceptance capacity models based on the above equation are expressed below for different arrival headway distributions.

Akcelik – M3D Model:

For the Akcelik – M3D model, the bunched exponential distribution is used with the bunching model to determine φ_m using Δ_m and k_d.

$$Q_g = \left(\frac{3600}{t_f}\right)\left(1 - \Delta_m q_m + 0.5\varphi_m q_m t_f\right)e^{-\lambda(t_c - \Delta_m)}$$

Akcelik – M3T Model:

For the Akcelik - M3T model, the bunched exponential distribution is used with the Tanner bunching model to determine φ_m.

$$Q_g = \left(\frac{3600}{t_f}\right)(1 - \Delta_m q_m)\left(1 + 0.5 q_m t_f\right)e^{-q_m(t_c - \Delta_m)}$$

Akcelik – M1 Model:

For the Akcelik – M1 model, the simple negative exponential model of headway distribution is assumed using $\Delta_m = 0$, $\varphi_m = 1.0$ and $\lambda = q_m$.

$$Q_g = \left(\frac{3600}{t_f}\right)\left(1 + 0.5q_m t_f\right)e^{-q_m t_c}$$

Akcelik – M2 Model:

For Akcelik – M2 model, the shifted negative exponential model of headway distribution is assumed using $\varphi_m = 1.0$ and $\lambda = q_m/(1-\Delta_m q_m)$.

$$Q_g = \left(\frac{3600}{t_f}\right)\left(1 - \Delta_m q_m + 0.5q_m t_f\right)e^{-q_m(t_c-\Delta_m)/(1-\Delta_m q_m)}$$

4.4 Performance Analysis:

4.4.1 Level of Service (LOS):

It is the qualitative measurement considering operational condition within the traffic stream. Such as time, travel, speed, freedom to manoeuver, traffic interruption, comfort and convenience. Basically, it measures the traffic quality service. In this thesis, the LOS is based upon Average Control Delay (s/veh) in which "A" is the best condition and "F" is the worst condition.

The variation of LOS based on Average Control Delay is as shown in the table 4.3 below:

Table 4.3: LOS based on Average Control Delay

Level of Service (LOS)	Average Control Delay (s/veh)
A	0-10
B	>10-15
C	>15-20
D	>25-30
E	>35-40
F	>50

4.4.2 Degree of Saturation:

The degree of saturation of a rotary intersection is the measure of how much demand the roundabout is experiencing as compared to its total capacity. The degree of saturation (%) is the ratio of demand of each approach of the junction, with the value of 100% meaning that capacity and demand are equal and no further traffic is able to pass through the junction. The degree of saturation values over 85% are typically regarded as suffering from traffic congestion, with beginning of formation of queues of vehicles.

4.4.3 Average Control Delay:

Control delay is defined as the delay caused by a control device, either a STOP-sign or a traffic signal. It is approximately equal to the delay due to time-in-queue plus the deceleration-acceleration delay component. Delay measures can be defined for a single vehicle, as an average for all the vehicles over a specified time period, or as an aggregate total value for all vehicles over a specified time period. Aggregate delay is measured in total vehicle-seconds, vehicle-minutes, or vehicle-hours for all vehicles in the specified time interval.

The average control delay can be estimated for each lane of an approach of a roundabout as:

$$d = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{sq\left\{\frac{v}{c} - 1\right\} + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{450T}}\right]$$

Where: d = average control delay, (sec/veh)

v = flow in subject lane, (veh/h)

c = capacity of subject lane, (veh/h)

T = time period

Average control delay is a function of the capacity of the lane and its degree of saturation for any particular lane. The analytical model which is used to estimate average control delay assumes that there is no residual queue at the start of the analysis period. If the degree of saturation is greater than about 0.9, average control delay is significantly affected by the length of the analysis period.

4.4.4 QUEUE ESTIMATION:

Queue length is quite important while assessing the appropriateness of the geometric design of the roundabout approaches.

The average length of the queue can be calculated as per equation shown:

$$Q_{95} = 900T\left[\frac{v}{c} - 1 + \sqrt{sq\left\{1 - \frac{v}{c}\right\} + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{150T}}\right]\left(\frac{c}{3600}\right)$$

Where: Q_{95} = 95th percentile queue, veh

v = flow in subject lane, veh/h

c = capacity of subject lane, veh/h

Average queue length is equivalent to the vehicles-hours of delay per hour for an approach. It is useful in comparing performance of the roundabout with other intersecting forms, and other planning procedures that use intersection delay as an input.

Chapter 5

Result and Analysis

5.1 CAPACITY Analysis:

The capacity of the selected roundabout as found out from the methods discussed above are as shown in the table below:

5.1.1 FHWA Method:

The total vehicle flow obtained from the video data is first converted into PCUs by multiplying with suitable numbers for different types of vehicles for each of the four legs of the interested roundabout. Apart from this, total flow on circulatory headway is also obtained by analyzing the video data. Now, using FWHA equation of capacity estimation, the capacity of each of the leg of the roundabout is found out. The Degree of Saturation which is the ratio of volume to the capacity is found out. As the degree of saturation for each of the leg is found out to be less than 0.85, so the roundabout is said to be *Under Saturated.*

Table 5.1: Capacity and degree of saturation by FHWA method

Roundabout	Leg No.	Total Vehicle Flow	Total Vehicle Flow(PCU)	Total flow on circulatory headway	Capacity	Degree of Saturation
Vazhuthacaud Square Trivandrum	N	1370	701.3	1199.6	1565.20	0.448
	S	2725	1456	325.9	2190.69	0.665
	E	491	276.3	939.1	1751.70	0.158
	W	1860	998.8	1171.8	1585.11	0.630

5.1.2 IRC method:

The IRC method of capacity estimation is based on the geometric features of the roundabout which includes entry width, width and length of weaving section, diameter of central island etc. the capacity for each of the leg is found out to be higher than that computed from FWHA equations. The degree of saturation is well below 0.85 to conclude that the roundabout is *Under Saturated.*

Table 5.2: Capacity and degree of saturation by IRC method

Roundabout	Leg No.	Entry Width(e)	Width of Weaving Section(w)	Length of Weaving Section(l)	Capacity	Degree of Saturation
Vazhuthacaud Square Trivandrum	N	8.0	10.2	32.55	2794.54	0.251
	S	9.4	13.25	34.57	3514.98	0.414
	E	9.1	15.50	27.54	3379.33	0.111
	W	9.9	14.6	23.43	3240.24	0.308

5.1.3 AKCELIK model:

According to Akcelik, the capacity of any roundabout is a function of the opposing flow rate. Besides opposing flow rate, certain parameters such as average intrabunch headway, critical gap, follow-up headway, proportion of free unbunched vehicles etc. has also been considered. Considering 5 minute time interval, opposing flow rate has been found out for each interval for each of the leg. Now, capacity is estimated for each of the four Akcelik models corresponding to the opposing flow rate for every 5 minute interval. The comparison of all the four Akcelik models has been shown through graphs for each of the leg separately.

1. Akcelik – M3D Model:

According to the Akcelik M3D model, the capacity and opposing flow rate for each of the approach leg is as shown in the table 5.3 below:

Table 5.3: Capacity of each approach leg by Akcelik M3D model

Time lag (min)	N		S		E		W	
	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)
0-5	.237	763.9	.259	738.60	.07	986.20	.153	868.66
5-10	.159	860.72	.334	658.48	.093	952.13	.221	782.83
10-15	.213	792.48	.33	662.53	.078	974.22	.207	799.78
15-20	.17	846.36	.291	703.30	.091	955.04	.226	776.87
20-25	.198	810.87	.315	677.93	.09	956.50	.242	758.08
25-30	.221	782.83	.305	688.39	.078	974.21	.193	817.10
30-35	.231	770.94	.334	658.48	.088	959.43	.223	780.44
35-40	.222	781.63	.325	667.62	.076	977.20	.206	801.01
40-45	.217	787.64	.298	695.80	.085	963.84	.233	768.59
45-50	.228	774.49	.279	716.34	.086	962.37	.245	754.60
50-55	.236	765.07	.321	671.73	.079	972.73	.227	775.68
55-60	.232	769.77	.318	674.82	.076	977.20	.22	784.03

2. Akcelik M3T Model:

According to the Akcelik M3T model, the capacity and opposing flow rate for each of the approach leg is as shown in the table 5.3 below:

Table 5.4: Capacity by Akcelik M3T model

Time lag (min)	N		S		E		W	
	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)
0-5	.237	848.10	.259	735.74	.07	1335.08	.153	972.55
5-10	.159	1034.57	.334	585.60	.093	1269.36	.221	797.56
10-15	.213	903.06	.33	593.02	.078	1312.02	.207	831.60
15-20	.17	1006.90	.291	668.77	.091	1275.00	.226	785.65
20-25	.198	938.50	.315	621.41	.09	1277.83	.242	748.38
25-30	.221	884.50	.305	640.85	.078	1312.02	.193	866.66
30-35	.231	861.64	.334	585.60	.088	1283.50	.223	792.78
35-40	.222	882.20	.325	602.38	.076	1317.77	.206	834.08
40-45	.217	893.75	.298	654.71	.085	1292.02	.233	769.19
45-50	.228	868.45	.279	693.37	.086	1289.18	.245	741.54
50-55	.236	850.34	.321	609.94	.079	1309.16	.227	783.28
55-60	.232	859.37	.318	615.65	.076	1317.77	.22	799.96

3. Akcelik M1 Model:

According to the Akcelik M1 model, the capacity and opposing flow rate for each of the approach leg is as shown in the table 5.3 below:

Table 5.5: Capacity by Akcelik M1 model

Time lag (min)	N		S		E		W	
	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)
0-5	.237	876.99	.259	766.34	.07	1338.51	.153	985.33
5-10	.159	1049.33	.334	629.61	.093	1275.23	.221	820.82
10-15	.213	927.33	.33	636.32	.078	1316.24	.207	852.60
15-20	.17	1023.48	.291	705.11	.091	1280.64	.226	809.73
20-25	.198	959.99	.315	662.04	.09	1283.35	.242	775.10
25-30	.221	910.29	.305	679.70	.078	1316.24	.193	885.44
30-35	.231	889.36	.334	629.61	.088	1288.79	.223	816.37
35-40	.222	908.18	.325	644.79	.076	1321.78	.206	854.91
40-45	.217	918.78	.298	692.30	.085	1296.98	.233	794.41
45-50	.228	895.60	.279	727.55	.086	1294.25	.245	768.75
50-55	.236	879.04	.321	651.64	.079	1313.48	.227	807.52
55-60	.232	887.28	.318	656.82	.076	1321.78	.22	823.06

4. Akcelik M2 Model:

According to the Akcelik M1 model, the capacity and opposing flow rate for each of the approach leg is as shown in the table 5.3 below:

Table 5.6: Capacity by Akcelik M2 model

Time lag (min)	**N**		**S**		**E**		**W**	
	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)	Opposing flow rate (Pcu/sec)	Capacity Q (pcu)
0-5	.237	766.85	.259	634.99	.07	1327.40	.153	928.79
5-10	.159	995.61	.334	439.77	.093	1255.82	.221	714.77
10-15	.213	835.89	.33	449.45	.078	1302.49	.207	757.32
15-20	.17	962.67	.291	548.33	.091	1262.04	.226	699.78
20-25	.198	879.71	.315	486.54	.09	1265.15	.242	652.60
25-30	.221	812.72	.305	511.93	.078	1302.49	.193	800.71
30-35	.231	783.98	.334	439.77	.088	1271.37	.223	708.76
35-40	.222	809.84	.325	461.68	.076	1308.71	.206	760.40
40-45	.217	824.29	.298	530.00	.085	1280.70	.233	678.99
45-50	.228	792.57	.279	580.28	.086	1277.59	.245	643.89
50-55	.236	769.70	.321	471.56	.079	1299.37	.227	696.80
55-60	.232	781.17	.318	479.03	.076	1308.71	.22	717.78

5.2 PERFORMANCE Analysis:

As we found earlier that the roundabout is *Under Saturated* from every considered model, some more performance analysis has been done. The queue for each of the approach leg was found out to be within limits and the corresponding average control delay for the roundabout was well below 10 which suggests that the Level of Service for each of the leg of the roundabout was satisfactory and can be graded A.

Table 5.7: Queue, Delay & LOS for each leg

Approach leg	Queue (veh)	Control Delay (sec/veh)	Level of Service (LOS)
N	2.42	4.164	A
S	5.852	4.8826	A
E	0.5614	2.44	A
W	5.0244	6.1177	A

5.3 COMPARISON BETWEEN DIFFERENT AKCELIK MODELS:

A graph between capacity and opposing flow rate has been drawn for each of the four legs for the comparison of the Akcelik models. For comparison, linear regression was performed between Akcelik models and the results have been shown in the graphs below:

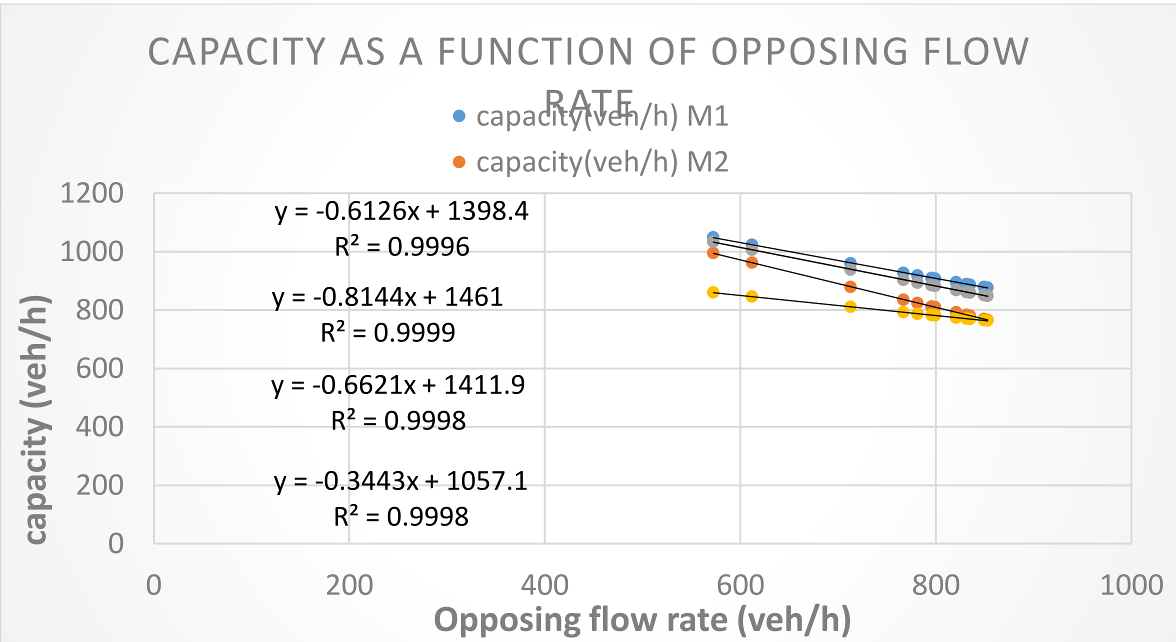


Figure 5.1: Capacity vs opposing flow rate for North leg

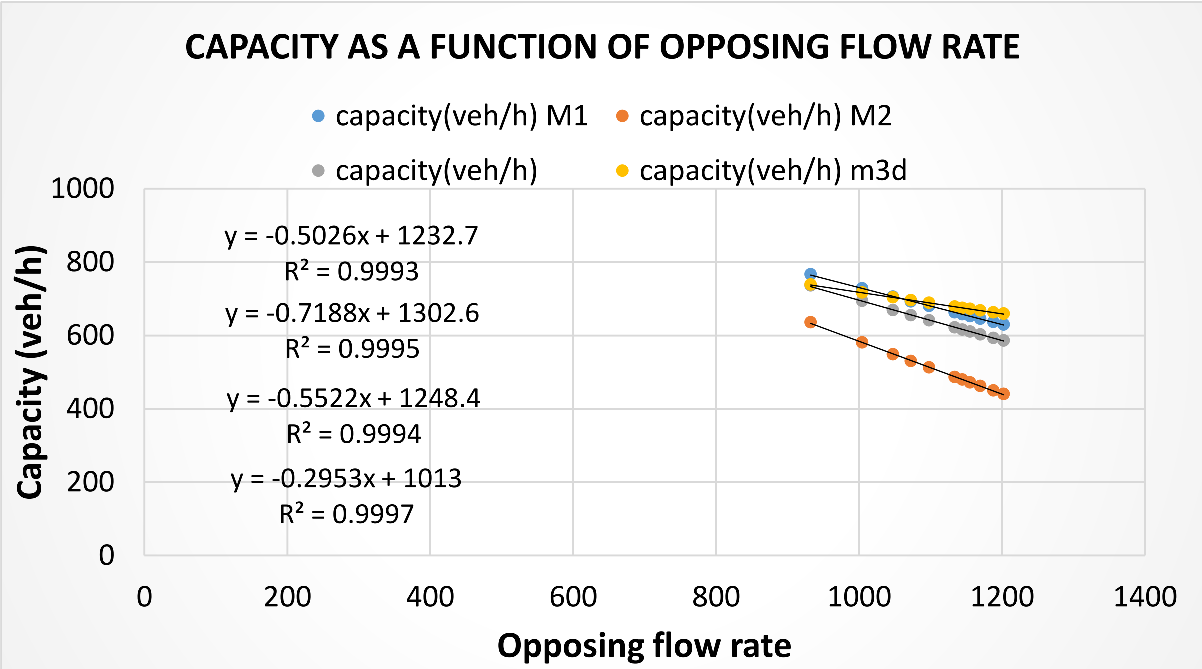


Figure 5.2: Capacity vs opposing flow rate for South leg

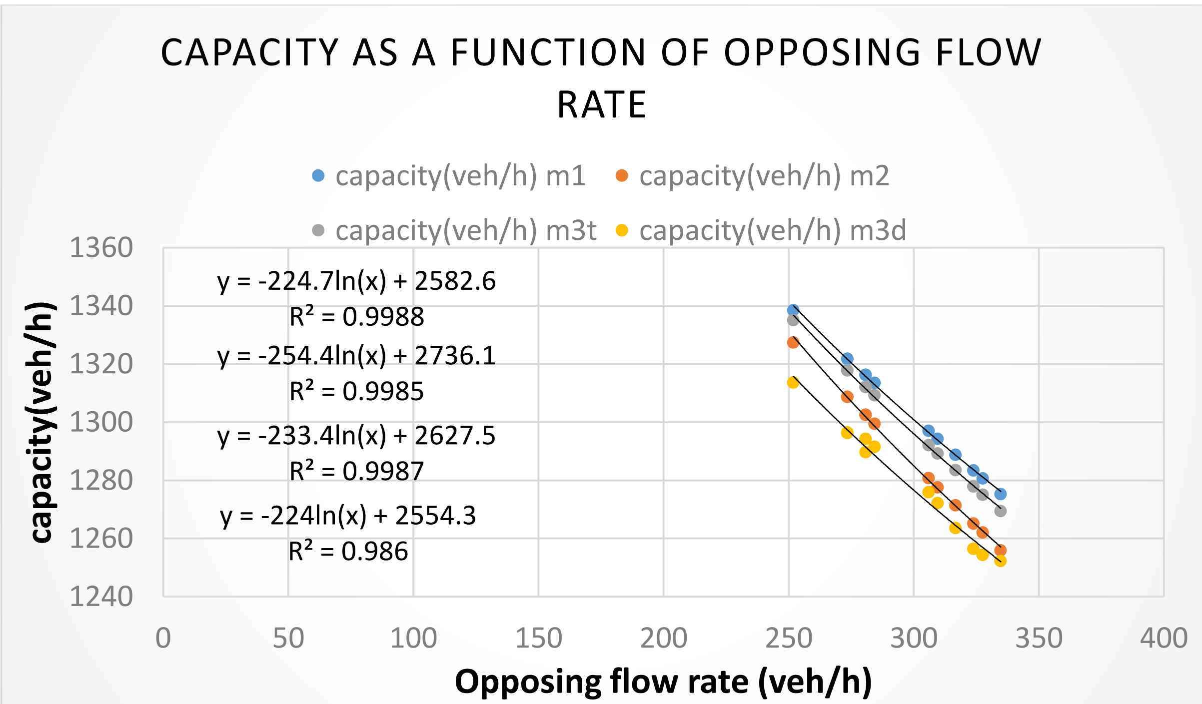
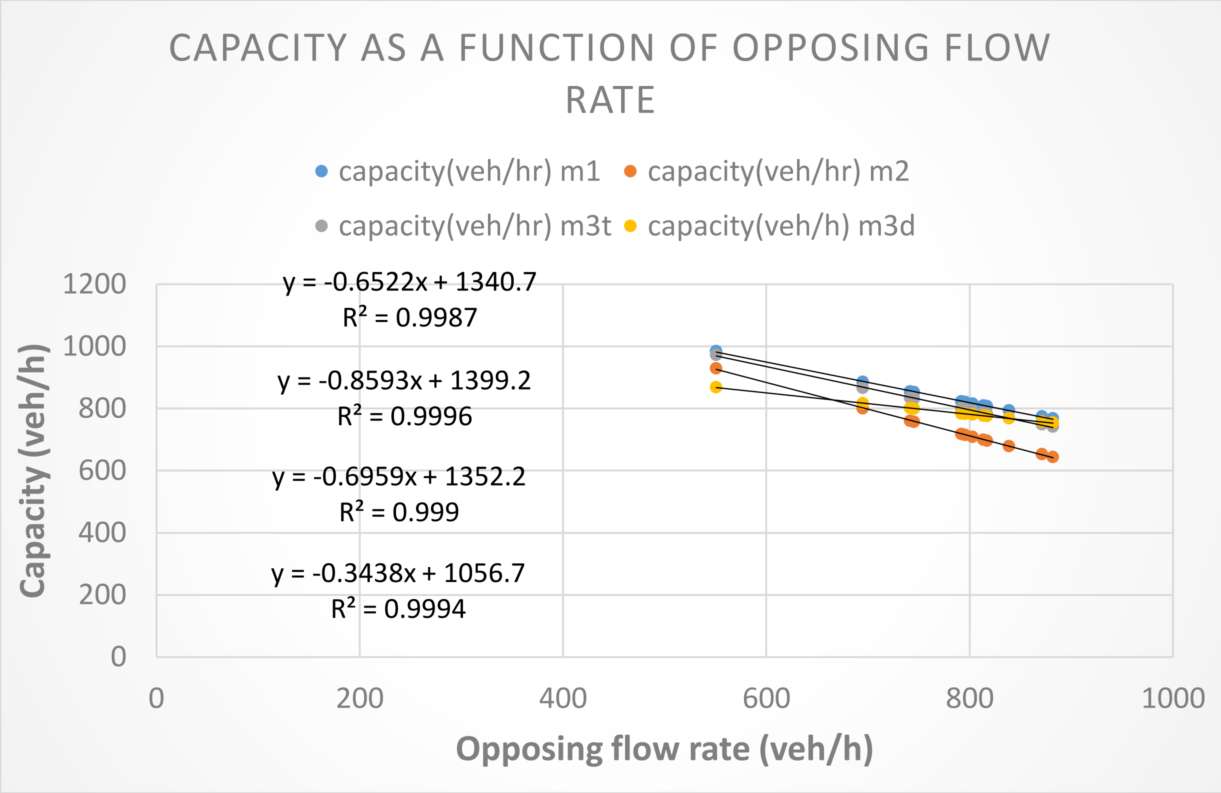


Figure 5.3: Capacity vs opposing flow rate for East leg



Graph 5.4: Capacity vs opposing flow rate for West leg

Chapter 6

Conclusions and Future Scope

6.1 Conclusion

In this research, there are various limitation to current methodologies for capacity and performance analysis in Indian context and various iterative procedure has been made to analyze urban streets in Indian context. The concept of urban street classification based on free-flow speeds, function and geometric characteristics of street segments are presented. Substantial differences in capacity estimates for congested roundabouts were observed between various tested international methods. Such differences make the judgement of accepting or rejecting certain capacity estimates very difficult. Limited geometric parameters have significant influence on the capacity of large roundabout during forced flow condition. These include number of entry and circulating lanes, approach entry width, width of the circulating travel way, width of Splitter Island and radius of Central Island. It was determined that analyzing the approach lanes on a lane-by-lane basis was most appropriate for my formulation. The other methods for determining the utilization of different entry lanes would be difficult or inaccurate to use a travel forecasting model.

Analyzing the roundabout showed that the roundabout is still in the under saturated condition as the degree of saturation for each leg of the roundabout from the considered methodologies has been found to be within 85%. Further, the Akcelik models showed a good relation of the capacity with the opposing flow rate which suggests that the considered roundabout is satisfactorily working.

On further performance analysis of the roundabout, the average control delay for each of the leg was found to be within 10 which signifies that the Level of Service for each of the leg was found to be in good condition.

6.2 Limitation and Future Scope

There are some limitations in this research work and further study can be carried out to overcome these limitations.

- The research is carried out only for the city of Trivandrum and this research can be further executed in other cities to analyze capacity and performance analysis of roads due to heterogeneous of traffic flow, road condition of other cities and driving characteristics.
- Capacity and Level of Service (LOS) is the prime component for the operational analysis of roundabouts. More data collection is required for analysis of roundabouts with signalized and un-signalized intersections.

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